ECL 162A

Engineering Case Library

VARIABLE STABILITY SYSTEM OF THE X-14A VTOL AIRCRAFT (A)

The first of two parts of this case describes the original control system and reasons for adding a variable-stability auxiliary system to the Bell X-14 experimental aircraft. By means of excerpts from the original project notebook the student is provided with information required to calculate thrust response of the aircraft. The second part includes the project notebook calculations for part one and poses the additional problems of writing a preliminary progress report, designing a simulator for the control system, and drawing a block diagram of the control system.

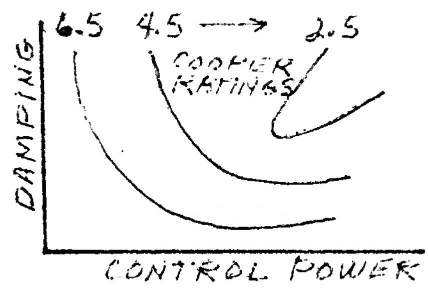
Prepared in the Design Division of the Department of Mechanical Engineering by J. Hill, G. Kardos, and A. Winn under the direction of Karl H. Vesper with financial support from the National Science Foundation.

VARIABLE STABILITY SYSTEM OF THE X-14A VTOL AIRCRAFT (A)

In early January 1960 Mr. Frank Pauli was summarizing the progress of the engineering design team composed of Pauli and Dan Hegarty, electrical engineers, and Tom Walsh, a mechanical engineer, all members of the Guidance and Control Branch of the Ames Research Center, at Moffett Field, California. Pauli concluded one of their frequent meetings with the observation, "I believe our most pressing problem will be the design of our nozzles to provide the right thrust within the limits of available bleed-air from the new engines to meet the pitch, roll and yaw acceleration specifications given to us last month."

The Ames Research Center, part of NASA, is charged with research into aircraft guidance and control systems, including both technological and physiological aspects. The Center is equipped with a full range of wind tunnels of various sizes and wind velocities, a sophisticated hybrid computer installation, several large aircraft and spacecraft simulators, and aircraft flight test facilities. Given the appropriate dynamic characteristics, the computers can be used to program the simulators to represent the response of high speed aircraft or spacecraft with up to six degrees of freedom (three translational and three rotational).

Pilot ratings of the effectiveness of a control system are given on a scale of ten (Cooper rating system), one being ideal and ten a "bail-out" condition; four can be flown but is unsatisfactory; five and six are unacceptable for normal operation. To explore a wide range of damping vs. control power curves the mission given the design group by Flight Operations and Flight Research Branches specified desired pitch, yaw, and roll accelerations of 5, 3 and 10 radians per second-squared respectively. These specifications are based on previous experience with helicopters.



In 1959 Ames Research Center acquired the Bell X-14 experimental vertical take off and landing (VTOL) aircraft for research purposes. After preliminary tests Flight Research and Flight Operations Branches requested the Guidance and Control Systems Branch to design and produce a system to provide variable damping for enhanced stability of the aircraft in the hovering mode.

The Variable-Stability Concept

In aircraft handling-qualities research, the ability to vary the fundamental aircraft parameters, such as damping and control power about each axis, and to vary or cancel the gyroscopic cross-coupling between the pitch and yaw axes resulting from the angular momentum of the engine rotors makes possible the evaluation of combinations of variables under realistic flight conditions. New concepts of handling qualities and the effect of changes in parameters may be readily investigated with an aircraft equipped with a

variable-stability control system.

It is proposed to accomplish this by means of state sensing and electronic computation to provide the necessary signals to augment the manual controls.

Such a control system is particularly valuable in the solution of stability and control problems in a VTOL plane where the inherent aerodynamic damping of the aircraft approaches zero as the flight velocity approaches zero and the aircraft attempts to hover. Research has shown that the ability of a pilot to control a system depends on the damping and control parameters. It follows that the choice of these parameters is exceedingly important for VTOL aircraft, since the aircraft takes off and lands in the hovering mode with no forward velocity, is close to the ground during these periods, and any loss of control almost inevitably leads to a crash.

The X-14A equipped with variable-stability control is, therefore, a research tool intended to provide insight into the methods which may be used to make VTOL operation of aircraft safer with less pilot fatigue and less total power requirements. Exhibit A-1 shows the X-14A in hovering flight.

The Original Control System

The Bell X-14 VTOL is a fixed-wing, jet-propelled, deflected-jet airplane in which the exhaust from the jet engines passes through diverters which enable the pilot to select any condition between horizontal and vertical thrust, or to make a transition from one to the other in flight.

The original control system provided direct control by the pilot of pitch, roll, and yaw through air jet nozzles at the tail and wing tips for control of the plane during hovering flight. These nozzles are mechanically connected to the stick and pedals and discharge air bled from the compressors of the turbo-jet engines to produce thrust.

The pitch nozzle is located in the tail and has ports both top and bottom (Exhibit A-2). The total exit area of the ports remains constant, for constant air flow, but rotation of the inner element provides a differential area to provide a net thrust up or down and so producing a pitching moment. The wing tip nozzles have a constant combined exit area. These nozzles are normally directed downwards. Axial movement of the nozzles changes the relative areas thus producing a rolling moment. A yawing moment is produced by rotating the wing tip nozzles in opposite directions about the lateral axis of the aircraft, one nozzle having a forward thrust component and the other nozzle having a backward thrust component.

Since diverting control air from the engines changes their thrust, and a change in thrust during delicate maneuvering could well cause disaster, the total air used by the control nozzles must be maintained constant, thus the necessity to maintain constant exit area of the nozzle system.

The basic X-14 has gyroscopic cross-coupling between the pitch and yaw axes due to the angular momentum of the engine rotors. For example, a pitch-up motion causes a left yawing moment proportional to the pitching rate of the aircraft. Conversely a yawing motion produces a pitching moment. This coupling limits the relative values of yaw and pitch rates.

To decide on steps to be taken in continuation of the project, Pauli was reviewing the project note book (see Exhibit A-3, 1 through 6) in which he had been recording all significant results of conferences, calculations and decisions of

the design group. Pauli noted that the available bleed air would be increased to 8.5 lbs/sec (for all control functions, both pilot controlled and servo controlled systems) by the replacement of the original Siddley Viper 8 engines with two GE J-85-5A engines. Tom Walsh had reported that there was room for additional 2½" ducts in the leading edge of each wing (alongside the present 3" ducts) and a new 4" duct probably could be installed in the fuselage to the tail. Dan Hegarty had determined that a type "O" servo system with magnetic power amplifiers could be easily adapted to drive 10 watt two-phase ac servo motors for V. S. nozzle control. Bell Aircraft had supplied its figures for moments of inertia of the aircraft. The General Electric Company had reported polar moments of inertia for gyro coupling effects and air temperatures of 524°F out of the engine. Finally the design group had decided on one new variable stability nozzle on each wing for roll control and two new nozzles (at right angles to each other) at the tail for pitch and yaw control.

"I wonder," Pauli thought, "if we can achieve the required degree of control with the available bleed-air supply. Also I wonder if 10 watt servo motors have enough torque to operate the nozzles satisfactorily. Finally how can we provide a fail-safe condition in case the servo system fails?"

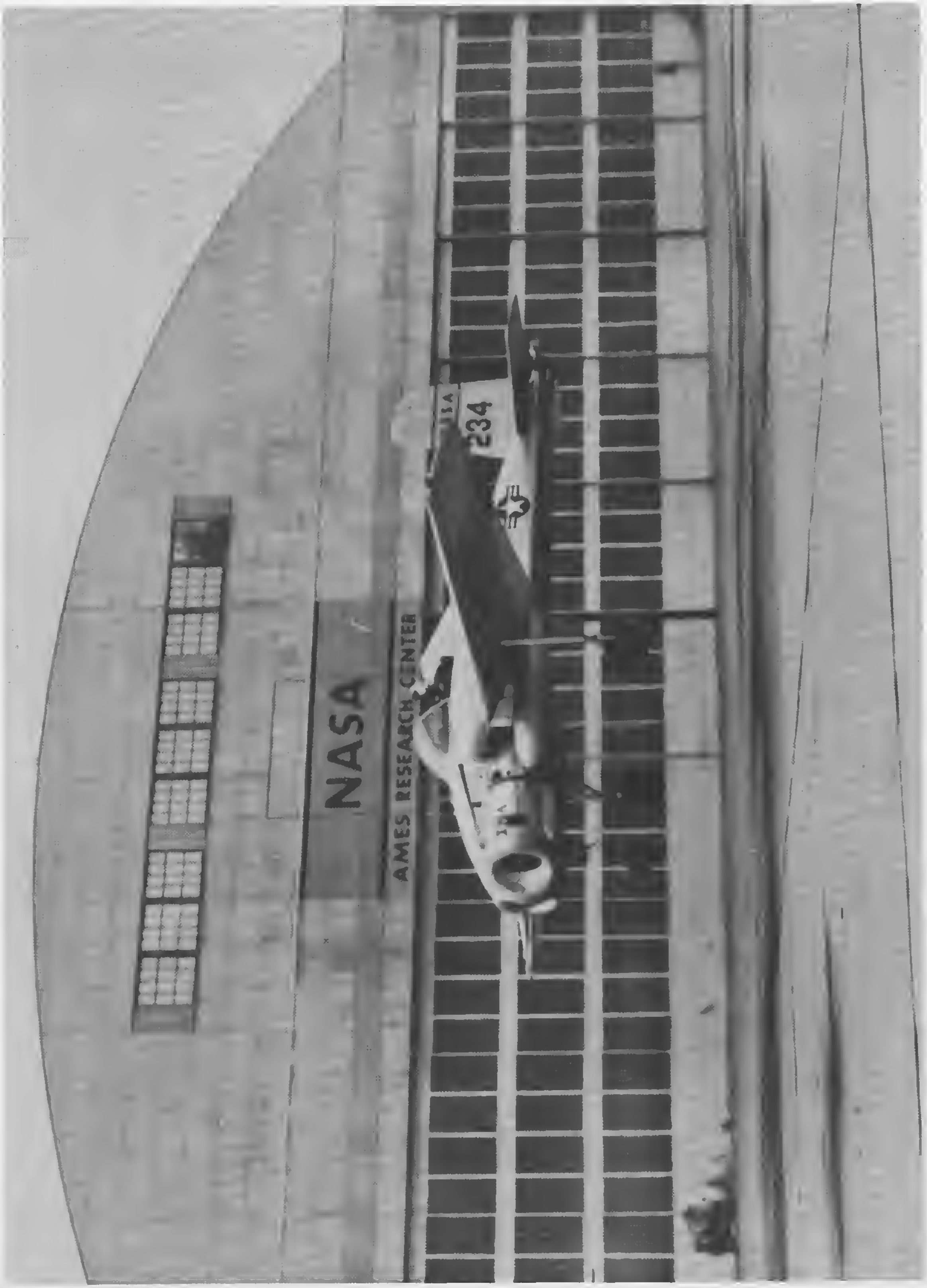


EXHIBIT A-1. Photograph of X-14 Hovering

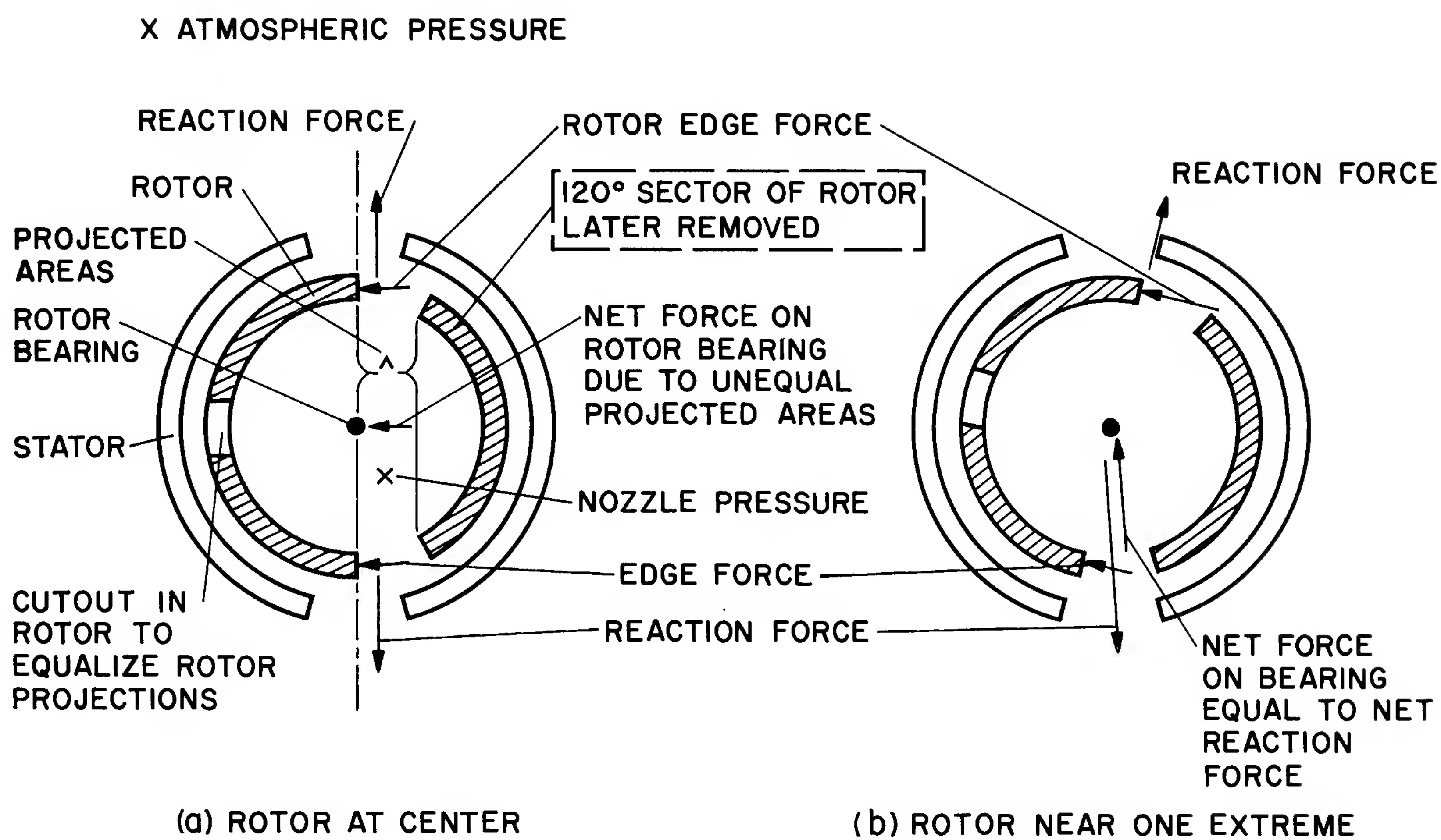


EXHIBIT A-2 · Forces Acting on a Prototype Nozzle

R 998 D Develop + install variable stability and variable control servo equipment in Bell X-14 vehicle.

Will provide adjustible control gearing about 3 axes, controlled artificial damping about 3 axes and controlled rate cross coupling. also height control damping, translational velocity control, and attitude control if practical.

Variable stability + Control VTOL/STOL

Accelerations

	Min. Accept.	Desirable
Translational modes		
fore + aft	± 9 ft/sec²	± 17
side	± 9	± 17
vertical	± 11	± 19
Rotational modes		
Roll	± 10 rad/sec²	± 10
Yaw	± 3	± 3
Pitch	± 5	± 5

1. Half rotational accel. capabilities reserved for pilot for safety reasons

2. Above for maneuvering + atmospheric turbulance inputs [order of 3 ft/sec² or .1 rad/sec² — May need more for dynamic response.

EXHIBIT A-3

Bell X-14 VTOL ~~#022~~ NEW #234 J.O. R-986-D 12-28-59

Prelim. meeting - Cooper, Drinkwater, Belsley, M. White, Anderson, A. Smith, Foster, Ratcliff, Thigpen, Walsh, Hegarty, Pauli

To make a variable stability VTOL in hovering mode.
(Must put new engines in to get excess control power.)

immediate objectives
A. Diminish amount of control to find min. acceptable.
B. Supply rate damping about each axis + be able to cross couple.
1) roll
2) pitch
3) yaw - of lesser importance
C. Put in altitude rate damping

later D. use position control
E. go into translational accelerations + rates.
(servo turning vanes)

Will also check while are in transition, i.e., too slow motion to be fully supported by wing or controlled by aerodynamics.

Have now 15°/sec max. yaw rate + in helicopters use 100°/sec + up to 360°/sec.

Now have 2900# = wt. incl. 40 gal. fuel (16 mins flight)
lift = 3200#
-300# = ground effect + diminishes to zero at 10 ft?

Will get J85-5A engines (G.E.) end Mar.?
← w/o afterburner.

J85-1 = mockup engine + for test of bleed air, etc end Jan.

J85's have 2000# thrust = 4000# total + weigh 400# less

Lear has used autopilot for position control. Report?

Can drive turning vanes of main engines through (±10°?) range in 5 secs. by motor + flex. shafts. This gives lateral accels.

Want 10% control override for pilot margin

In hovering there is no damping or restoring moment with angular displacement from trim attitude.

Can extend reaction tubes for increased lever arm within limits of bending.

Now have { $68^{\#}$ at wing tip + $0^{\#}$ at other
$25^{\#}$ at tail

Will get: $\approx$ 30 psi press + about $\underline{10^{\#}/sec}$ airflow $\underline{max}$. for control.

each J85 engine has $42^{\#}/sec$ + can divert about $10\% = 8.5^{\#}/sec$.

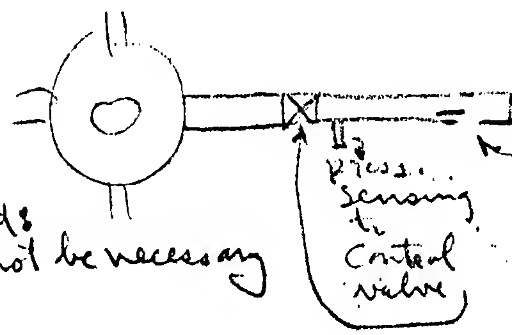
$10^{\#}/sec = 600^{\#}/min$. @ 30 psi 30 psi = 45 psia. or $3 \times \rho$

so free air $= 1800^{\#}/min$. $\underline{air = .07651^{\#}/cu ft.}$

$10^{\#}/sec = \frac{1800}{.07651} = 23{,}500$ CFM.

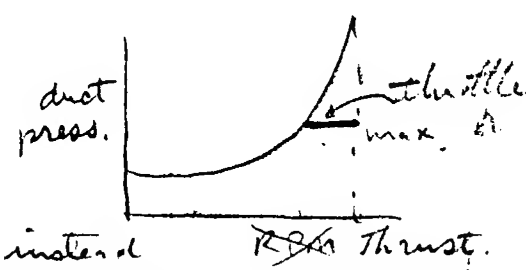
Reaction control pressure is constant over last 15% (10-15%) of control.

get constant reaction force with engine RPM



Freds may not be necessary

use 20% instead of 10% at max RPM. if throttle



use thrust control due to vertical velocity $= \dot{h}$
$h = 10 - 50$ ft

Seth: In flight RPM variation from 80.-100% of rated.

To. 2a. ω_z, ω_x, ω_y, then $\ddot{z}$
$\ddot{y}$, $\ddot{x}$, $\dot{y}$, + $\dot{x}$, etc. less important

Exhibit A-3

12-29-59

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Walsh - Cutout lever between turbine + plenum.

al Faye: Simulating present config:
present engines 2.2 #/sec total. = 3½% (4% max bleed)
yaw right + get pitch up. (Engine rotation CCW). Pitch up + yaw left
polar mom. of I = Ip = 24.24 (% RPM) slug ft²/sec
have 88% RPM for hovering + 2960# gross
- tell Str. + report. -

Quigley: Thrust changes proportional to amount of bleed air + not directly prop. to R.P.M.

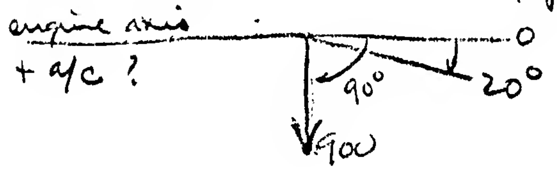
12-31-59

Drinkwater, Walsh + Pauli:
To see Bob Tejeon? in GE J85-5A engine.
Mock up engine = J85-1 for same physical mtg.
2 - J85-5A's to be 400# less than 2 Siddley Viper 8's.
YJ85-GE-5 T.O. 2J-J85-26 for maint.

yaw rate limited by pitch control - Vice versa but can't stand attitude to get large pitch rate with present moments.

yaw controls at max only affect lift by 2(34-28.8) ≐ 20# out of lift of 3000#, so negligible.

Turning vanes move only fore to aft, no sidewise components -

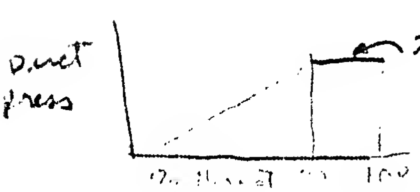


Thrust vector control. Can nose A/c up 70° + use 20° angles if wish.

No objection to yaw control on tail, but 1# on tail requires about 6# on nose to keep C.G. constant.

Only had a small battery in A/c + put another in (in parallel) No generator; might be able to get off engine pad.

Fred doesn't know if need throttling valve (F-100 #200 has one + seems simple) as he would be at constant alt. + const. power when taking data. Otherwise should throttle down above 90% thrust to remain constant



He may actually vary from 85% Thrust but 90-100 looks OK.

Exhibit A-3

Tom sent to library for Crim, also D report on V.S. A/c + also for damping info! from NASA TN-D-58 by Salmirs + Tapscott.

Crim gives accel reqd roll 150-200 deg/sec²
pitch 40-50
yaw 20

Siddley Viper 8 (ASV-9 compressor)

13,000 RPM Takeoff
13,500 hovering 30-32 psi } plenum press
5,500 idle 8 psi } pilots meter

Rolls' curve:

psi	RPM
24	12750
12	11000

slope = $\frac{12\,psi}{175\,RPM}$ = .0683 $\frac{psi}{RPM}$

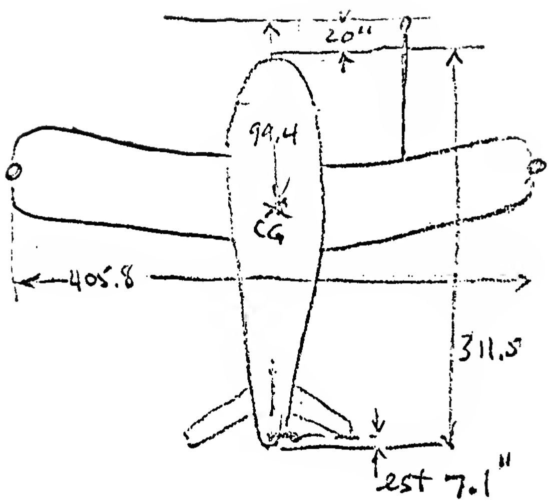
Bell A/c letter of 10-26-59 to McEwen
Latest estimates 4-30-57 using theoretical press P2/14212 report 68-978-002, + also pitch duct static press, run 21-36.
pitch force 28.5# for 34.5 psi duct before enlarging orifice
dynamic time lag negligable for roll duct!

	force	arm	moment
Pitch	34.0#	18'	612 ft-lb.
Yaw	47.3	17	804
Roll no yaw	66.9	17	1137
max yaw	47.3	17	804

Config	Gross	I_x - slug ft²	I_y	I_z	ΣW_{xz} slug ft²
A/c no fuel	2626.8	1020.9	1947.2	2772.0	2493.7
73# fuel	2700	1052.5	1955.9	2798.4	2526.7
173	2800	1092.3	1967.6	2838.1	2578.1
273	2900	1131.1	1977.7	2877.4	2634.2
→ 373	3000	1169.2	1987.9	2917.7	2693.2
473	3100	1205.1	1996.3	2958.3	2756.7
573# fuel	3200	1240.4	2007.8	3002.9	2825.3

fuel density = 6.35 $\frac{lb}{gal}$ each tank cap = 46 gals = 492#

(12-31-59)



Semi-span = 202.9" = 16.9'.

Tail leverarm: 311.5 + 20 − 99.4 − 7.1

$$\begin{array}{r} 331.5 \\ 106.5 \\ \hline 225'' \end{array} = 18.75$$

46 gal max ea. tank
6.35#/gal
492# max ea tank or 984# total

$T = I\alpha$

yaw
desired = 20 deg/sec²

$804 = \alpha_z \cdot 2917.7 \qquad \alpha_z = \frac{804}{2917.7} = .276\ \frac{rad}{sec^2} = \underline{15.8\ \frac{deg}{sec^2}}$

pitch
desired = 40-50 °/sec²

$\alpha_y = \frac{612}{1987.9} = .308\ \frac{rad}{sec^2} = \underline{17.6\ \frac{deg}{sec^2}}$

roll
desired - 150-200 °/sec²

$\alpha_x = \frac{804}{1169.2} = .688\ \frac{rad}{sec^2} = \underline{39.5\ °/sec^2}$ MIN.

$\frac{1137}{1169.2} = .973 = \underline{55.6\ deg/sec^2}$ MAX.

	present: split	present: max #/sec	present: max moment	new engine: #/sec	new engine: max moment	1-4-60: 3-orifices split	1-4-60: moment
Pitch	1/3	.7	.7	3.3	3.3	1/5	2
Roll	2/3 (Roll + Yaw)	1.5 (Roll + Yaw)	1.5 } w/t simult.	6.7 (Roll + Yaw)	6.7 } w/l simult.	2/5	4
Yaw			1.05 } w/t simult.		4.7 } w/l simult.	2/5	4
				10.		← pitch ½ others.	10

gyroscopic factor + pitch or yaw rates needed give moments needed on other axes

If use 10% override = 5.24 pilot + 4.76 Als.
pilot cmd has 1.5#/sec for yaw (as 1.05 now gives nearly enough accel)
+ leaves 3.75 for pitch + roll.
for x3 on pitch accel + takes 2.0 + leaves only 1.75 for roll

ECL 162B

ENGINEERING CASE LIBRARY

VARIABLE STABILITY SYSTEM OF THE X-14A VTOL AIRCRAFT (B)

On January 18, an informal meeting was held to review the progress of J. O. (Job Order) R-986-D, the development and installation of a variable stability system in the X-14. This job had been initiated in late December. "Dr. Smith has asked me to submit a progress report to go with next year's budget. I have a fair summary of what we've done since the beginning in my lab book,"[1] said Frank Pauli.

Prepared in the Design Division of the Department of Mechanical Engineering by J. Hill, G. Kardos, and A. Winn under the direction of Karl H. Vesper with financial support from the National Science Foundation.

"Is this a fail-safe feature?" asked Cooper.

"Yes," replied Pauli.

"You've got my pressure drop calculations there, haven't you, Frank?" asked Walsh.

"Yes, and I have worked out the resultant performance figures from them," replied Pauli.

"That brings us up to date," continued Pauli. "I will need further information to complete the report, particularly a projection of our activities. I haven't anything on the simulator; could you let me have something on how you propose to do the simulation, Al? Tom, do you feel that the nozzle will give us any more trouble or are the answers straightforward? I know we've done servo systems before and they should offer no difficulty but for the report we had better include a diagram on how we intend to build the system."

Frank Pauli received the advice and comments from his colleagues at this meeting and prepared his progress report.

1-4-60

$T_{yaw} = H \times \omega_{pitch}$

H present $= 24.24 \times (\% RPM) = 2424.$ slug ft²/sec = lb ft sec

$T_{pitch} = 612$

$\omega_{yaw} = \frac{612}{2424}$ rad/sec = 14.4 °/sec. + is present limit!

anderson, Rolls, Smith, Foster, Hegarty, Walsh, Pauli.

anderson = VTOL/STOL

Quigley
Welch
Rolls
Turner

M. White = Simulation

Faye
Gerdes.

Rolls 8.25#/sec. + duct vel. < 300 ft/sec.
new engine = 90 psi.

N.G.

	desired		will get	force
roll	16 rad/sec²	5	6.6 rad/sec²	220#
pitch	~~8~~	2.5	2.9	318
yaw	~~3~~	1.5	2	cos 45° · 220

} 540# = total reaction force.

½ for pilot + ½ for V.S.

Tietjon GE J85-5A engine
353# wt. ea. (may not include all fittings)

	Mil	Normal
Thrust	2250	2000
RPM	16050	15,600

Polar moment = 12.4 lb ft² @ 100% RPM.

(old engines) 1.11 #/hr. / # thrust — Specific fuel Consumption = SFC = .923 #/hr / # thrust

main engine air = 42.5 #/sec @ 100% RPM
bleed 6% for specs. To check for 10%.
Press. ratio = 7.
Can get generator for engine pad mtg.

J85-5 gives 2500#/engine.
[illegible] full 2250

1-5-60

Armstrong Siddley Viper 8 engine -(J. W. Morris safe)

525# wt.

	RPM	Thrust	Fuel gal/hr.	SFC #/#/hr.
idle	5500	155	57	2.63
med	8000	370	77	1.665
high	13,100	1600	224	1.117
100	13,800	1900	270	1.135

Rotor I = 27 lb-ft^2 [polar inertia? 200 lb ft^2] – whole engine?

gyro couple = 1225 lb ft at 13,800 RPM + turning rate of 1 rad/sec.

$$H = \frac{27}{32.2} \cdot \frac{2\pi \cdot 13{,}800}{60} \times \overset{\text{two engines}}{2} = \underline{2424} \quad @ \underline{100\% \text{ RPM.}}$$

J85 – Takes ignition power of 115V 400 ~ 75 VA / engine.

Takes JP-4 = 6.5#/gal.

See Par 8-1 TO 2J-J85-6 (Inspectors safe under Tietjen).

idle = 72% = 11,500 RPM. 830-975 #/hr. = fuel

$I = 12.4$ lb ft^2 @ 100% RPM = ~~15,600~~ 16,500

$$H = \frac{12.4}{32.2} \cdot \frac{15{,}600 \cdot 2\pi}{60} \times \overset{\text{2 engines}}{2} = \underline{1260 \ @ \ 100\% \text{ RPM.}}$$

$\boxed{H = \frac{15.9}{32.2} \cdot \frac{16500 \cdot 2\pi}{60} \cdot 2 = 1330}$ at 100% = 1250 @ 94% 2-61

$\boxed{15.9}$ Rolls to Selmer on 2-4-60

$$H = \frac{lb\ ft^2\ sec^2}{ft} \cdot \frac{Rev}{Min} \cdot \frac{Min}{Sec} \cdot \frac{Rad}{Rev} = lb\ ft\ sec. \qquad H\omega_p = lb\ ft$$

So new engines will only have $\frac{1260}{2424}$ = 52% of gyro cross coupling.

$T = I\alpha \qquad \alpha = T/I \qquad \omega = \alpha t + \omega_0 \qquad \theta = \frac{\alpha t^2}{2} + \omega_0 t + \theta_0$

if $\theta = 30°$ max = .5 rad. + $\alpha = 5 \frac{rad}{sec^2}$

$.5 = \frac{5 \cdot t^2}{2} \qquad t^2 = \frac{1}{5} = .2 \qquad t = .45$ sec, to get to θ = .5 rad.

+ while so doing $\omega = 5 \cdot .45 = 2.5 \frac{rad}{sec} = 150°/sec. = \omega_p$ max.

ω_y max = 60 – 90 °/sec.

Exhibit B-1

1-6-60

Checked Roll's figures (see P 7 mid) + reaction forces check but not accels.

Got together with Anderson, Rolls, Walsh, Hegarty + Paul + decided to give all reaction forces to axes so to get relative roll, pitch, + yaw accels. of 10, 5, 3 rad/sec².

Rolls was going to have wing tip + access plate taken off so we could decide if it is feasible to put a larger or another duct in wing. This will put limitation on type of system we will use.

Y = yaw force $\quad \alpha_y$ = yaw accel. $\quad \dot{w}_y$ = #/sec air for yaw
R = roll ✓ $\quad \alpha_R$ = roll ✓ $\quad \dot{w}_R$ = ✓ ✓ ✓ roll
P = pitch ✓ $\quad \alpha_p$ = pitch ✓ $\quad \dot{w}_p$ = ✓ ✓ ✓ pitch.

If have 8.5 #/sec air total, want to divide it to give pilot 10% override on each V.S. axis and want pilot to be able to cmd accels. of $\alpha_R, \alpha_p, \alpha_y$ in ratio of 10, 5, + 3.

Orig. I-mess.
roll .67
pitch = .31
yaw = .28

1-7-60

Put Pilot yaw + roll + V.S roll on wing
Pilot pitch and V.S. pitch + yaw on tail

Present $\alpha_r = \dfrac{68^{\#} \cdot 16.9'}{1170 \text{ slug ft}^2} = .981 \text{ rad/sec}^2$

$\alpha_y = \dfrac{68 \cdot .707 \cdot 16.9}{2920} = .278 \dfrac{\text{rad}}{\text{sec}^2}$ $\qquad \dfrac{\alpha_y}{\alpha_r} = \dfrac{.278}{.981} = .284$
(use this + not .3)

$\alpha_r = 1.0\ \alpha_r$
$\alpha_p = .5\ \alpha_r$
$\alpha_y = .284\ \alpha_r$

Pilot $\quad$ P + R = pilot cmd $\quad T = I\alpha = F \cdot L \quad F = \dfrac{I\alpha}{L}$

$P = \dfrac{1990 \cdot .5\alpha_r}{18.75} = 53.1\ \alpha_r$ $\qquad Y = \dfrac{.284\ \alpha_r \cdot 2920}{16.9} = 49.1\ \alpha_r$

$R = \dfrac{\alpha_r \cdot 1170}{16.9} = 69.2\ \alpha_r$ $\qquad .707\ R = .707 \cdot 69.2 = 48.9\ \alpha_r$ ✓

PILOT. ACCELS. — Rad/sec² 1-8-60

	present	desire	expect	% desire	x present
Roll	.973	5	1.91	38.2	1.97
Pitch	.307	2.5	.957	38.2	3.12
yaw	.275	1.5	.541	36.1%	1.97

$\Big\{$ 3.2" D in wing / 3.33" D in Tail for 300'/sec

$\alpha_p = \alpha_p$ $\quad \omega_p = \alpha_p t + \omega_0$ $\quad \theta_p = \frac{\alpha_p t^2}{2} + \omega_0 t + \theta_0$

$30° = .5 = \frac{1}{2}\alpha t^2 \quad \alpha_p = .957 \quad t^2 = \frac{1.0}{.957} = 1.043$

$t = 1.02$ sec.

$\omega_p = .957 \cdot 1.02 = 1 \frac{rad}{sec} \approx 60°/sec.$ = max ω_p expected before pilot gets to attitude > 30°.

Have 520# reaction force. If $\alpha_r = 5.0$ $M = 5 \cdot 1170 = 5850$

$R = \frac{5850}{16.9} = 346$ # so need 66% of total.

Present duct orifice areas

tail = 29/64 × 1.88 = .852 sq ins max.

wing = .84 × 2.00 = 1.68 sq ins max.

tail = $\frac{.852}{2.532}$ = 33.6% .74 #/sec ≐ 74·45.9 = 33.9 #T

wing = $\frac{1.68}{2.532}$ = 66.4% 1.46 #/sec ≐ 1.46·45.9 = 67.1 #T

2.20 #/sec. 101.0 #T

Air Unit: Multipurpose A/c ground service unit
type MA-2 T.O. 35C1-3-3-11. field svc.
14 parts cat (Anderson)

4" hose part no = 367-002 - Navy Available.

MA-2 @ 360°F 50 psia. 125#/min or 110#/min depending on model.

Pod = 90#/min.

New engine 984° R = 524° F } air temp.
old engine 838° R = 378° F } out of engine

at 500 ft/sec in present 3" duct get 8# press. loss base on 1.5 #/sec = 1.445 psi drop + is prop. to (in)²

1-7-60

VS = 3 orifice

$P + R + Y = V.S.$ $\qquad \alpha_{r_{V.S.}} = .90\, \alpha_{r_{pilot}}$

$$P = \frac{.5\alpha_r \cdot .90 \cdot 1990}{18.75} = 47.8\,\alpha_r$$

$$R = \frac{.90\alpha_r \cdot 1170}{16.9} = 62.3\,\alpha_r$$

$$Y = \frac{.284\,\alpha_r \cdot .90 \cdot 2920}{18.75} = 39.8\,\alpha_r$$

on tail → 18.75

Total reaction force = 520# = pilot + V.S. = 272.2 α_r

$\alpha_r = 1.91$ rad/sec² $\qquad$ 8.5#/sec air gives 520# thrust

1#/sec = 61.2#

pilot

R = 1.91 · 69.2 = 132# = 2.16#/sec
P = 1.91 · 53.1 = 101.5 = 1.66 #/sec
Y = 132 · .707 = 93.4 = 1.53 #/sec

tail duct = $P_p + VS_p + VS_y$
1.66 + 1.49 + 1.24 = 4.39#/sec

V.S. R = 1.91 · 62.3 = 119# = 1.94 #/sec
P = 1.91 · 47.8 = 91.4# = 1.49 #/sec.
Y = 1.91 · 39.8 = 76.1# = 1.24 #/sec
520.0# $\qquad$ 8.49 #/sec.

wing duct = $P_R + VS_R$
2.16 + 1.94 = 4.10 #/sec.

8.49 #/sec

	Present system + engine							New engine + 3 V.S. orifices. 10% Pilot override									
								Pilot					V.S.				
	I	M	L	F	α	.01% α_r	#/sec	F	L	M	α	#/sec	F	L	M	α	#/sec.
Roll	1170	1137	17	67	.973	1.00	1.0	132	16.9	2230	1.91	2.16	119	16.9	2010	1.72	1.94
Pitch	1990	612	18	34	.307	.316	.5	101.5	18.75	1905	.957	1.66	91.4	18.75	1715	.862	1.49
Yaw	2920	804	17	47.2	.275	.284	—	93.4	16.9	1580	.541	1.53	76.1	18.75	1426	.488	1.24
							1.5					3.82					4.67
																	3.82
																	8.49

H = 2424 @ 100% RPM

$H\omega_y = M_p \qquad \omega_y = \frac{612}{2424} = .252\ \frac{rad}{sec} = 14.4°/sec$

$\omega_p = \frac{M_y}{H} = \frac{804}{2424} = .331\ \frac{rad}{sec} = 19.\ °/sec.$

1.5#/sec = 67 + 34 = 101#T $\qquad$ 1#/sec = 67.5#T

1#/sec = 61.2#T.

H = ~~1260~~ 1330 @ 100% RPM

$\omega_y = \frac{1905}{1260} = 1.51\ \frac{rad}{sec} = 86.5°/sec$ no V.S.

$= \frac{3620}{1260} = 2.87 \qquad = 164$ with V.S.

$\omega_p = \frac{1580}{1260} = 1.26 \qquad = 72°/sec$ no V.S.

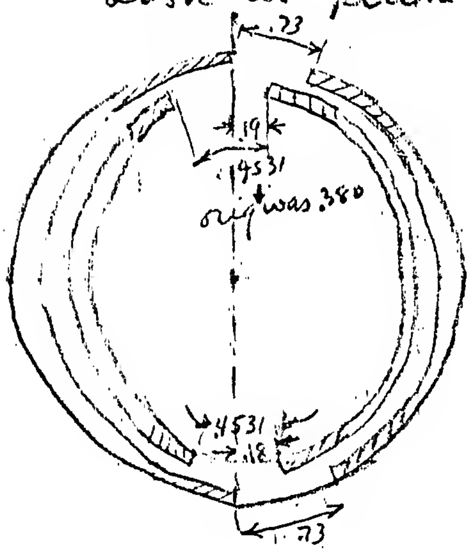
$= 2.38 \qquad = 136°/sec$ with V.S. 10

Meeting: Anderson, Rolls, Campbell, Selam, Smith, Foster, Hegarty, Walsh, Pauli.

E.D. to look at wing + see if can get in larger ducts. Our accelerations on proposed systems are OK for now but Top should be informed. Harper to be informed on need for another man from E.D. for duct work.
To try and get P ± V.S. by inflight adj.

Rolls: presently about 1.5#/sec in airflow
max. rates: roll 180°/sec, pitch 60°/sec, yaw 60°/sec } for ordering rate gyros.

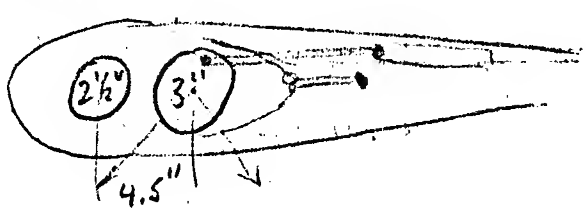
Look at pitch orifice: Trim tabs for pitch only. Preset on aileron

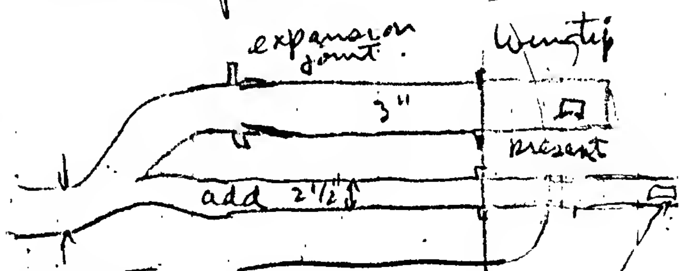


Looks like inner ring opening was symmetrical at .380 about dia. Then enlarged it on one side (fwd) on top + bottom.
This gives present system + if need max. Close one .453 - .18 - .19 = .083" before other is completely open. This doesn't give const. bleed at last part of opening

1-12-60

Selam: Can put additional 2½" D duct in wing! Wing tip is off + shows up as easily done. Present input pipe is 3" O.D. + feeds 3" I.D. in wing.





$A = \frac{\pi D^2}{4} = \frac{\pi}{4}(9 + 6.25) = \frac{\pi}{4}(15.25)$

$A = \frac{\pi}{4}(3.9)^2$ .. 3.9" = equiv D of 3" + 2.5" ducts.

1-12-60 (cont.)

Jake finds present rate gyros in X-14 are:
Gianini pot pickoff d-c motor + not too good.

roll = ±1.5 rad/sec		3.0	estimated need.
pitch = ±5	✓	1.0	
yaw = ±.25	✓	1.0	

Figure to put in 3 new gyros for servo + put in buffer + demod. for recording sigs.

1-13-60

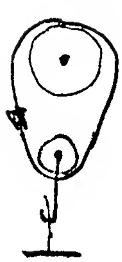
H. Clark to order 2 Doelcam K-37 ±60°/sec rate gyros for me, to be delivered before 2nd Feb.
Looked into motor, rate gen, gear reduction units + looks like 1st step is to meas. torques on present controls with MA-2 unit

1-14-60

Got spare pitch orifice. Sort of binding so to Kelly to smooth. Also design of adapter by Walsh to Kelly to use with MA-2 test of nozzle. Took linkage off orifice on plane + is very low torque except when open all on top where gets some binding.
Got 100 psi press meter + also force indicator to meas. torque. Will try + meas. reaction force also by setting unit on spring scale.

1-15-60

Ran some tests on spare pitch nozzle for torque. Lever arm = 2.25". Used roller pully on A/c cable for normal load.



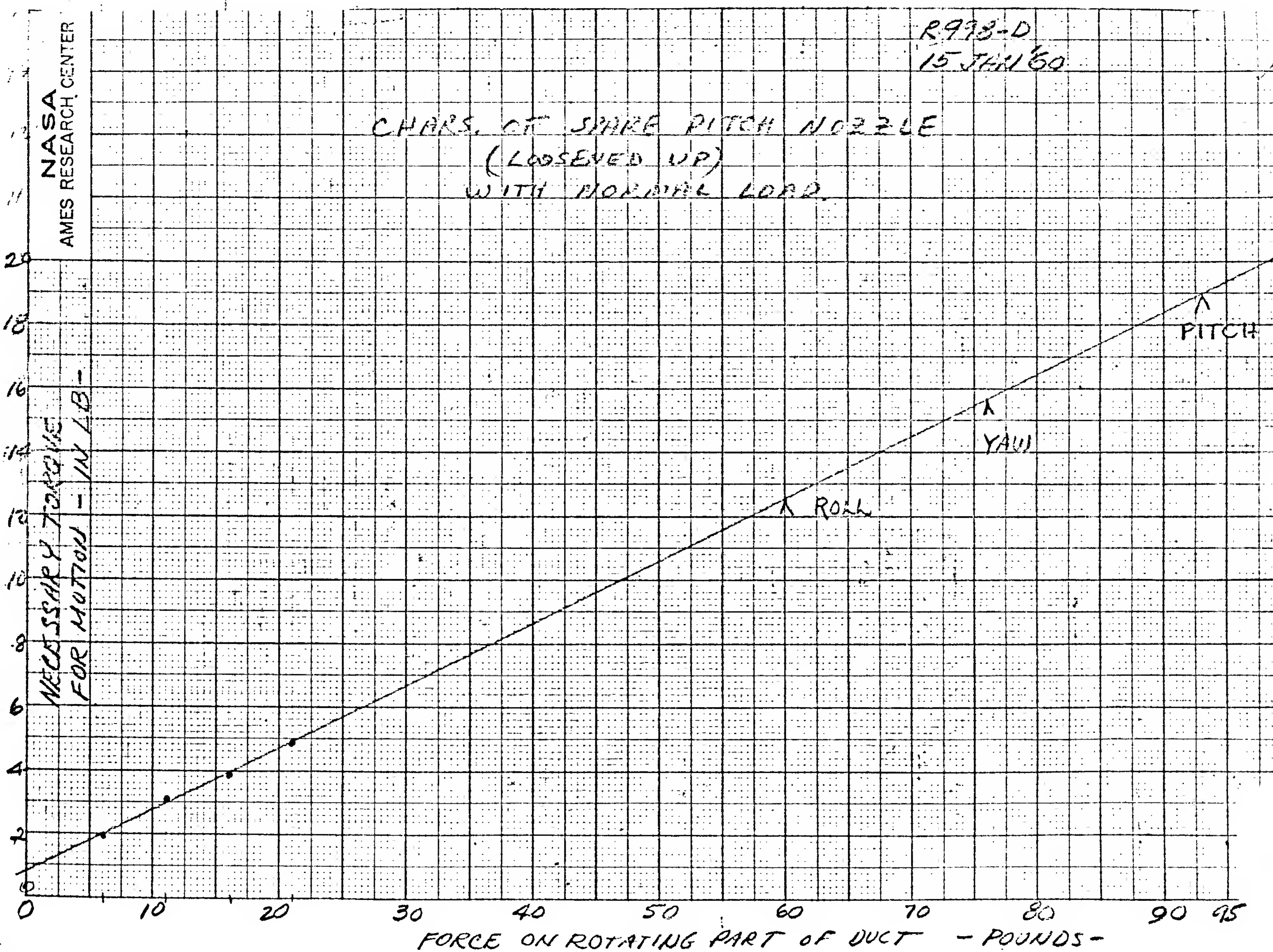
Force-lbs	.125	6	11	16	21
Normal load-lbs	0				
Torque-lb-ins	.283	1.9	3.1	3.9	4.9

Nozzle supported by plate screwed to flange of nozzle.

Extrapolate out (see curve next page) + looks like about 20 in-lbs req'd for proposed system. This req's too much gearing to get desired torque + somewhat marginal even on a 16 W motor. If tests on nozzle confirm this will have to redesign nozzle for low friction + so may be able to use 5 or 10 W motor.

$$\text{Thrust } T = \frac{\rho}{g} V^2 A = \frac{\dot{w} V}{g} = \dot{m} V$$

$\rho \approx P \quad V = K$ for $P > 13.7$ psi



14

Exhibit B-1

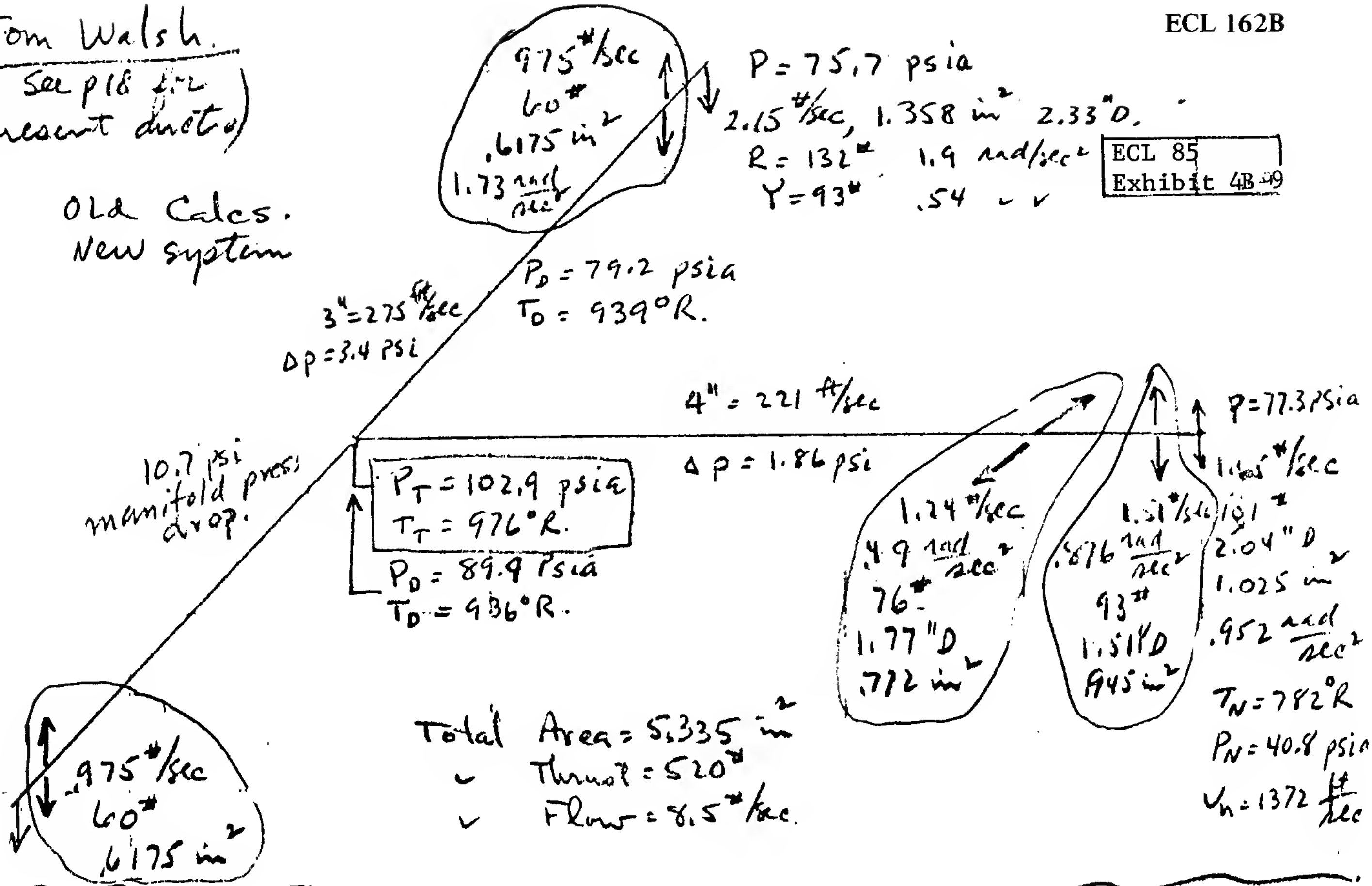
1-18-60

Tom Walsh

(See p18 for present ducts)

ECL 85
Exhibit 4B-9

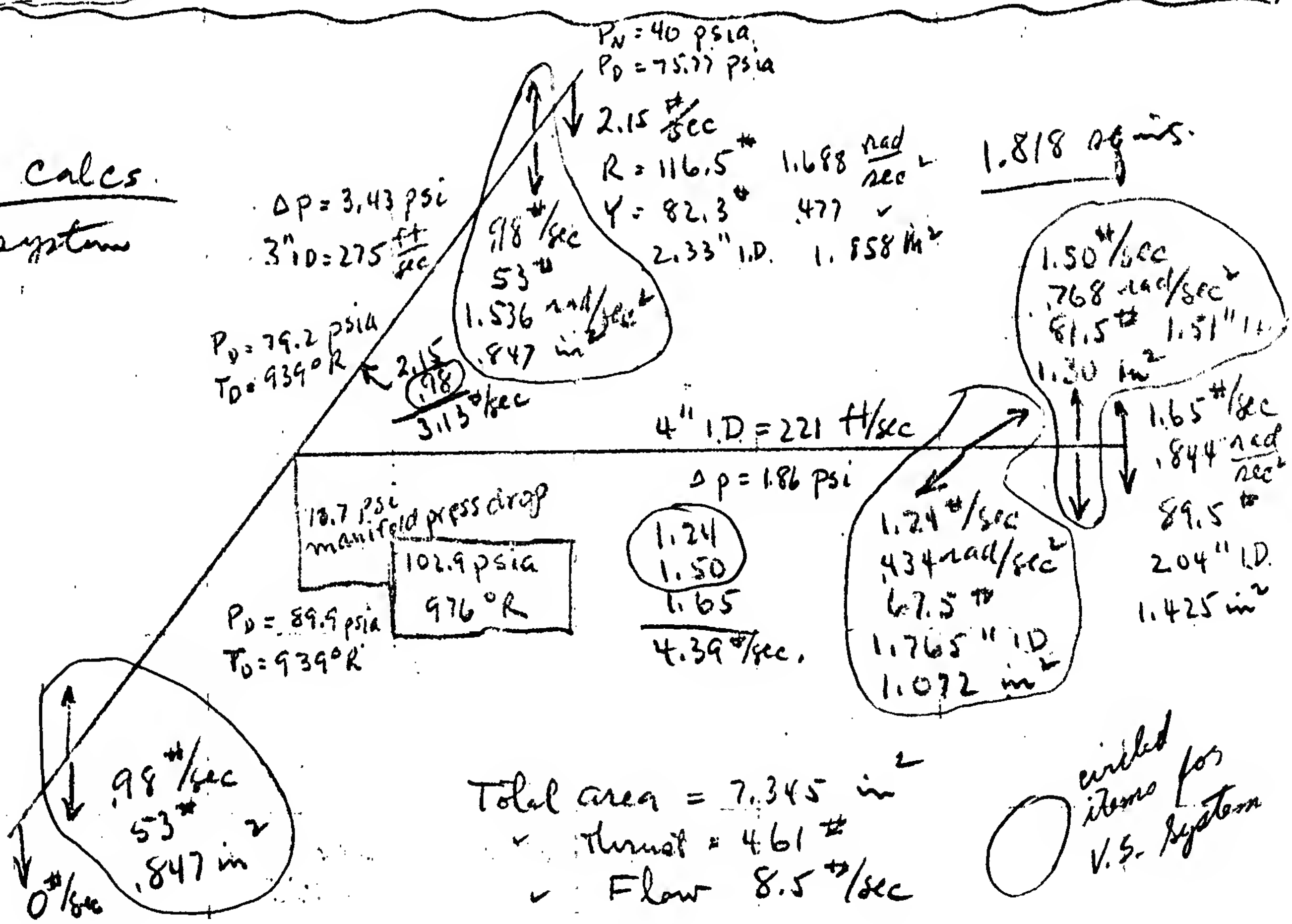
Old Calcs.
New system



Total Area = 5.335 in²
✓ Thrust = 520#
✓ Flow = 8.5 #/sec.

Best Calcs.
new system

1.818 sq in.



Total area = 7.345 in²
✓ Thrust = 461#
✓ Flow 8.5 #/sec

circled items for V.S. System

1-18-60

Called Selan. He will check tube lengths req'd for wing + tail so we can order (reserve stock). Got adapter late but all set up now. To try scale from Hanger #1 – Rec. + Ship have 70# platform scale we can borrow for short time.
Hash over acceler, etc on motors.

1-19-60

Hook MA-2 to orig. pitch nozzle. Set for equal openings top + bottom, take out tare on scale.

	Air.	nozzle	tare	scale	°C	Press gage	Force on 2¼" arm.
①	off	½	45	0	room	0	2 oz.
	on	½	45	0	55	42	2⅞ lb.
	off	½	40	0	room	0	2 oz.
②	on	½	40	3	–	–	–
	on	full	40	35	73	44	≈ 3 lbs.
upside down on nozzles lever arm underneath ③	off	½	29	0	–	–	–
	on	½	24	0			
		near full	24	–			5# not move to full open!

.38" × 1.88" = .7144 sq ins = total area orifice.
at 44psi get 44 · .7144 = 31.43 lbs. compared to 32 above. Compares to 34# in pitch from Bell letter, but don't know what pressure had or even area as could have been .453 × 1.88 = new nozzle.

2211 Tubeway, LA, 22

Selan called on ducting. Stock tubes are .12" wall + too heavy for us. Tubesales Co in L.A. has .035" wall in 2.5 + 3" O.D. + .065" wall in 4" OD. Present is Al of 1/32" wall.
Order 3" OD × .035" wall (1015) cold drawn seamless steel tubing.
Price – scale down stock cat, Elect weld 4" D = .049" wall.
Reserve? Gressler or Mays

Want for A/c.	40'	3" OD	2-15' + 1-10'	$2.00/ft	have 100'
	40'	2.5" OD	2-15' + 1-10	$1.50/ft	193'
	24'	4" OD	2-15'	$3.00/ft.	505'

for mockup use stock tubing + need 2-20' 2" OD
1 20' 3¼" OD.

not continuous

Tubesales Co. 2211 Tubeway St. LA, 22, Calif.

APPENDIX

FORMULAS AND CALCULATIONS FOR REACTION NOZZLES

In this appendix pertinent symbols and formulas are given. Calculations are made to establish the various nozzle forces.

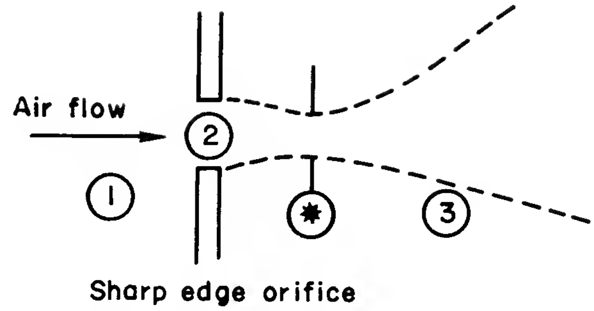
SYMBOLS

A	cross-sectional area, sq ft
C_d	discharge coefficient ratio, A_*/A
C_v	velocity coefficient
F	reaction force of pilot nozzle, lb
F'	reaction force of variable-stability nozzle, lb
g	acceleration of gravity, 32.2 ft/sec^2
I	moment of inertia, slug-ft^2
L	moment arm, ft
$\dot{m}$	mass flow rate, slugs/sec
P	pressure, psia
R	universal gas constant
T	absolute temperature, $^{\circ}R$
V	flow velocity, ft/sec
$\dot{w}$	pounds flow rate, lb/sec
α	angular acceleration, rad/sec^2
γ	ratio of specific heats at constant pressure to constant volume and equal to 1.4 for air
ρ	density, slugs/cu ft

Exhibit B-2

Subscripts

1	located upstream
2	located at orifice
3	downstream
*	position of sonic velocity
p	pitch
r	roll
t	tail
w	wing tip
y	yaw



TOTAL NOZZLE EXIT AREA CALCULATED FOR ALL BLEED AIR

Mass flow rate can be expressed as:

$$\dot{m}_* = \rho_* V_* A_*$$

and

$$\dot{w}_* = g\dot{m}_* = g\rho_* V_* A_*$$

From the perfect gas laws it can be shown that:

$$\dot{m}_* = \frac{\sqrt{\gamma} P_1}{\sqrt{RT_1}} \left(\frac{P_*}{P_1}\right)^{\frac{\gamma+1}{2\gamma}} C_d A_2$$

Using an experimentally determined C_d of 0.90 and knowing the ratio of $P_*/P_1 = 0.5283$ at Mach 1.0 (see ref. 5)

$$A_2 = \frac{\dot{w}_* \sqrt{T_1}}{0.4767\ P_1}$$

From engine data, $\dot{w}_* = 8.5$ lb/sec, $P_1 = 76$ psia, and $T_1 = 939^\circ$ R, so solving: $A_2 = 8.5\sqrt{939}/0.4767(76) = 7.17$ sq in. This is the total allowable exit area to keep the bleed flow desired.

Exhibit B-2

TOTAL REACTION FORCE AVAILABLE FROM ALL NOZZLES

The total reaction force, ideally, can be expressed as:

$$F = \dot{m}_* V_* + A_*(P_* - P_3)$$

Because of friction at the orifice edge, V_* will not be obtained over the whole area A_*, but will be less at the outer edges of the flow stream. This, in effect, reduces the sonic throat area to give an average area of sonic flow of $C_V A_*$, so actually,

$$F = \dot{m}_* V_* + C_V A_*(P_* - P_3)$$

Using the relationships $\dot{m}_* = \rho_* A_* V_* C_V$, $(V_*)^2 = \gamma R T_*$, and $P_* = \rho_* R T_*$, and keeping sonic flow:

$$F = C_V C_d A_2 P_1 \left(1.268 - \frac{P_3}{P_1}\right)$$

With $C_V = 0.95$ from test data and P_3 as atmospheric pressure, $F = (0.95)(0.90)(7.17)(76)[1.268 - (14.7/76)] = 500.7$ pounds total reaction force.

VARIABLE STABILITY SYSTEM OF THE X-14A VTOL AIRCRAFT (B)

"The requirements by Flight Research Branch asked for everything they could use, we soon found them to be impossible. Using the data forwarded by Bell Aircraft we were able to determine the torques and forces in the present system," Frank said, pointing to page 5 of his lab notes (exhibit A-3, page 5). "We hoped these would satisfy Crim's requirements, but they didn't. This, of course, was with the Viper engines. We also calculated the cross coupling. The new G. E. engines to be installed will give us more thrust.

"As you remember we split the project into two parts; some of you are working on the aircraft hardware and the rest on the simulating of the aircraft response on the ground. As soon as the hardware is available it will have to be tested.

"Mr. Rolls recalculated the roll accelerations using the figures received from G. E. for the two J 85-5A engines; 8.25 lbs/sec at 90 psig air from the compressor. With this we could, we thought, get 5 rad/sec^2 in roll, 2.5 rad/sec^2 in pitch, and 1.5 rad/sec^2 in yaw. We proposed to divide this equally between pilot control and the V. S. system."

"I thought we had agreed that there would be an override for the pilot?" interjected Cooper, the chief test pilot. "If the V. S. system fails we have to be able to fly it down manually."

"You know that safety is always foremost in our minds, George," replied Pauli. "We did agree on a 10% override for the manual control, although I'm not certain that will be enough in all cases.

"Since we cannot achieve the desired rotational accelerations, we had better try to maintain the original ratios, 10:5:3. I've rerun the calculations on this basis.

"With respect to the nozzles to be used on the V. S. system, we are being pushed for time, therefore we agreed that using the basic concept of the existing pitch nozzle would be best. This nozzle was selected because it is a constant bleed nozzle. This eliminates any engine problems due to variable bleed. It also has linear characteristics. Its reactions are known and, frankly, we can't think of anything better at this time.

"The arrangement of the nozzles has now been changed from that of the manual system. We will have the V. S. roll nozzles in the wing tips, and the pitch and yaw V. S. nozzles in the tail. Rolls has had a look at the aircraft and we have room for additional ducts in the wings, but we may not be able to fit the necessary ducts into the tail."

"We may have trouble with those nozzles," commented Walsh. "The spare nozzle we received had a sort of binding, you recall. We cleared it for the pressures we could test at, but it still may be a problem."

"Yes, I know," said Pauli. "We also seem to have a problem with torques. The figures you gave me indicate that our servo motors won't be able to handle it. I gather this is not entirely a balancing problem. I think we'll have to redesign this, keeping only the basic concept."

"The nozzles should have a zero reaction when the power to the servos is cut," said Walsh.

[1]See Exhibit B-1 for reproduction of notebook.

INSTRUCTOR'S NOTES

Variable Stability System of the X-14A VTOL Aircraft

This case covers the early stages of the development of a variable response system for the X-14.

The initial attraction of the case to the authors was the fact that F. Pauli kept an excellent notebook on the progress of the project. This is a trait highly desirable in any engineer but woefully lacking in most. Mr. Pauli's notebook is reproduced as exhibits in the case and the case is so constructed that the exhibits are an integral part of the case. With an introductory reading of the printed portion, the notebook should be studied to extract the technical details and the development of the project. From this, class discussion can be developed on:

1. Merit of good records
2. Purpose of engineering log or records
3. Positive features of Pauli's notes
4. Negative features of Pauli's notes

The purposes of the exercise would be to have the student recognize the need for good engineering records and to induce him to use them in the future.

The technical aspects of the case may be used to exercise the student's understanding of elementary mechanics. The X-14A, in a hovering mode, presents us with a close approximation of a free body. The following questions, although apparently trivial, can be used to examine the student's ability to extend formal mechanics to real life situations.

1. If the X-14 weighs 2600 lbs., what is the minimum vertical thrust required to hover? (neglecting ground effect)
2. Neglecting aerodynamic drag, what total thrust will be required to accelerate the vehicle vertically at 1 ft/sec^2?
3. If the moment of inertia of the X-14A about the roll axis is 1000 slug ft^2 and the control jets at the wing-tips are 17 ft apart, what reaction force is required at each wing-tip to produce a roll rate of $\pm$ 10 radian/sec^2?
4. What is cross-coupling?
5. What is cross-coupling due to in the X-14A?

For more advanced students in dynamics and controls, they could be asked to write the equations of motion of the X-14. They could also be asked to show how these would have to be modified to give the necessary variable response system.

The design of the control nozzles for the variable control system comes in for considerable attention from F. Pauli. The assessment of the design can be used as an exercise for design students.

Part B of the case is presented as a progress meeting between the principal participants. It is expected that this part of the case can be used to further examine the technical details of the case. At this point, the project has gone through one iteration and the performance requirements altered. The alterations and the reasons for them should come in for close scrutiny.

Assignments based on the first two parts of the case can be given:

1. Preparation of a progress report based on the meeting.
2. Design of a ground simulator to test the control system and nozzles. The specifications of the simulator requirements are critical.